Development of Quick Semisolid Slurry Making Method for Standard Casting Aluminum Alloys

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論文内容要旨

The semi-solid metal structure was invented in the early 1970's by Spencer and Flemings at MIT when investigating hot tearing with a rheometer. They found that by mechanically agitating a solidifying alloy in the solid-liquid temperature range, the solid phase would not be in the form of dendrites, but be spheroidal particles instead. Stirring breaks up the dendrites which are present normally so that the microstructure in the semi-solid state consists of spheroids of solid surrounded by liquid. The inventors discovered that the non-dendritic nature of the solid phase gave these metal "slurries" unique rheological properties. The inventors realized that if the metal slurries were formed into parts, the higher viscosity would lead to less turbulent mold filling, thereby producing high quality parts by minimizing the entrapment of air and inclusions.

The cutting edge research issues are now in developing the potential for producing high performance alloys and its concomitant requirement to obtain the method which does not have the disadvantages of semi-solid processing and including its advantages.

The ultimate goal of this research is finding the single-step manufacturing of components with various shapes, sound structural integrity, and properties comparable to the wrought state at low cost similar to castings. It is believed that this method (Cup-Cast method) emerges technology of semi-solid processing to satisfy most of the requirements.

In the first chapter there is a short review about semi-solid casting and advantage and disadvantage of this method comparing to other manufacturing processes.

In the second chapter Cup-Cast method was introduced. The cup-cast method that has been just developed is a novel process that make semi-solid casting as easy as pouring the water from a pitcher into a drinking glass, and avoid all the problem and difficulties of other semi-solid casting processes. Cup cast method is based on the heat and mass transfer and spherical equiaxed particles with controlling the nucleation and growth of solid particles were produced. This method employs the recently discovered criticality of the combination of rapid cooling and vigorous convection at the onset of solidification to create semi-solid slurry. This research was embodied the principle of this noble method and discussed Cup-Cast method from different approaches, temperature profile, nucleation and growth, and microstructure. The most important parameters those would be affect the slurry properties was mentioned and discussed.

It would be useful in this method suitable cup for specific alloy and condition can be predicted. These issues contribute to have less experimental observation for getting the desired condition. The third chapter was based on this fact. To this effort, dimensionless number γ has been used to determine the fraction solid and fraction solid variation. Firstly, the fraction solid was calculated as a function of γ . Secondly, by measuring the temperature and investigating the solid fraction variation effect of different parameter could be investigated. But there are some other parameters those govern semi-solid slurry properties in Cup-Cast method because of changing in heat and mass transfer in the melt which is one of the main principles of this method. Changing the dimension of the cup, cup's material and cup's design would be changed the solid fraction variation in the melt and slurry properties.

In Cup-Cast method, embryos of solid particles may, be created on the inner surface of the cup and evolutionary change to nuclei. These nuclei should easily be separated from the wall of the cup and move by the melt flow to the other part that may cause low temperature and composition gradient that derive non-dendritic growth. Different factors would affect on the shape and size of solid particles which was discussed on the forth chapter:

1. This study has demonstrated BN spray coating because of its nucleation site and easily separation of nuclei, and also control the heat transfer through cup's wall was the best coating.
2. Pouring height change the amount of turbulence in the melt that causes the uniform temperature distribution in the bulk liquid. The agitation prevents the formation of stable diffusion fields around solid particles that causes rounded globules without much growth. Microstructure analysis point out 40cm height of pouring make suitable turbulence in the melt and continuity in melt flow, but because of limitation in experimental procedure 10 cm Pouring height was set.
3. For pouring duration because of the two parallel factor that would be affect the slurry properties; amount of melt's turbulence and turbulence duration good slurry would be achieve at low pouring duration (10 sec) and high pouring duration (50sec). In this study 10 sec pouring duration was set because of experimental procedure.
4. At low pouring temperature, the under-cooled melt near the Cup's wall explodes with the large number of nuclei, big bang or copious nucleation. The floating of these nuclei towards the central regions establishes a uniform cooling rate through out the mold. The uniform cooling rate and large number of nuclei, promote the formation of good semi-solid structure. 620 °C pouring temperature was the best pouring temperature.

These results suggest that Cup-Cast method is a feasible new Semi-Solid casting method.

For more complicated simulation of this method, such as simulation with ADSTEFAN™ software, heat transfer coefficients at different point of the cup and melt and there effect are required. The fifth chapter was based on this fact. This method is based on the nucleation and growth of solid particles, and sufficient rest time (holding the isothermally in semi-solid sate), heat transfer phenomena will considerably influence on the semi-solid microstructure of this method. Based on the facts of this method those driven out from the temperature measurement a model for heat transfer in cup cast method was proposed. This analytical equation is in the good agreement with experiment at center and inside of cup's wall and is in the acceptable agreement with experiment at outside of cup's wall.

In aluminum industry the most important manufacturing root is die-casting method. If we can apply this semi-solid method to die-casting manufacturing root, it would be good way for making parts. So the sixth chapter is about combining Cup-Cast method with die-casting method and the result in making parts.

Cup-Cast method has been developed for the production of Al-alloy components with high integrity. Cup-Cast can be easily achieved by adding a robot machine and some cup to the existing cold chamber diecasting machine. The Cup-Cast samples have close to zero porosity, fine and uniform microstructure and are free from other casting defects. Compared with high pressure diecasting or any available semisolid processing techniques, Cup-Cast method offers components with improved strength and UTS, which can be attributed to micro-structural refinement and uniformity, much reduced or eliminated porosity and other casting defects, and refined and dispersed oxide particles. Other advantages of the Cup-Cast process include flexible with alloy compositions, more tolerant to Fe contents and lower overall production cost. Cup-Cast process is particularly suitable for production of high safety, airtight and highly stressed components in the automotive industry.

論文審査結果の要旨

アルミニウム合金鋳物を製造するための代表的な鋳造法としてダイカスト法がある。ダイカスト法で製造される鋳物（ダイカスト）は、鋳肌がきれいで大量生産が可能で安価であるという特長があるため、自動車用部品として多量に利用されている。しかし、空気の巻き込みなどの鋳造欠陥の発生を押さえるのが困難であるため、高品質なダイカストを製造するための特殊なダイカスト法が数多く提案されてきた。半凝固ダイカスト法は、その中の一つであり、固相と液相が混在した半凝固スラリーを金型に充填することで空気の巻き込みを押さえ、あまつさえ、金型への熱負荷を低減することで金型寿命が向上するという優れた鋳造法である。しかし、半凝固スラリーの作製に時間がかかるため、コストや生産性の点で問題があり広く普及するには至っていない。

本研究は、アルミニウム合金半凝固スラリーを迅速にかつ安価に製造するための新しい製造技術について基礎的検討を加えたもので、全編７章より成る。

第１章は緒論であり、今までに提案されている半凝固鋳造法を批判的に解説し、それぞれの特徴についてまとめ、実用化のためには何が必要かを述べている。

第２章では、金属製の容器を用いた新しいアルミニウム合金半凝固スラリー製造法について検討した結果について述べている。特に、微細な球状初晶を有する半凝固スラリーを短時間で製造できるメカニズムについて、核生成とその後の成長の観点から、測温実験結果を基に論じている。

第３章では、所定の固相率を有する半凝固スラリーを製造するために必要な金属製容器の熱的特性について検討した。まず、溶湯と金属容器の熱的特性について解析的な検討を加え、最適な製造条件を得るために重要な無次元パラメータを提案し、次に、代表的な鋳造用アルミニウム合金であるAC4CH,ADC10,AC2Aに対して、その有用性を実験的に検証している。

第４章では、本法により、微細な球状初晶を有する半凝固スラリーを得るための諸条件について実験的に検討し、金属容器形状、注湯高さ、注湯時間、注湯温度、離型剤の種類などについて最適な条件を得た。

第５章では、本法における金属容器及び溶湯の過渡温度特性について非定常伝熱解析により解析的に議論している。また、測温実験結果との比較により、スラリーと金属製容器の間ならびに空気と金属製容器の間の熱伝達係数を求めている。

第６章では、本法で作製した半凝固スラリーを用いてコールドチャンバーダイカスト機により試験片を実際に鋳造し、その機械的特性を調べた。その結果、引っ張り強さ、伸び、ガス量ともに優れた値を示していることを検証している。

第７章は、総括である。

以上要するに本論文は、アルミニウム合金ダイカスト法による自動車部品の製造を前提とした、新しい半凝固スラリー製造方法の可能性について理論と実験により検証したもので、金属フロンティア工学の発展に寄与するところ少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。